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Design of multilayer polarizing beam splitters using genetic algorithm

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Abstract

Polarizing beam splitters (PBSs) are key elements of optics and optical communication systems. In this paper, cubic and plate multilayer PBSs have been designed using genetic algorithm (GA) method which is a powerful optimization tool. In this work, after an introduction to genetic algorithm, a plate PBS has been designed using this method to show the ability of GA technique to design polarizing beam splitters with predefined target. Then, a GA-designed cubic PBS has been compared with a MacNeille one on the spectral characteristics and index profile. Finally, a C-band cubic PBS has been designed with GA and the results have been compared with ones obtained from needle, flip-flop and combined GA and gradient design methods with similar design parameters. The results show that the genetic algorithm method has the ability to design the thin film polarizing beam splitters and in comparison to other techniques has reasonable results when the time is not a critical parameter in the design process.
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Keywords: Polarizing beam splitter; Thin film filters; Genetic algorithm

1. Introduction

Polarizing beam splitters (PBSs) are optical filters that separate two orthogonal polarization components (S and P) of light into different directions. In these filters the S and P polarizations have equal importance. Wavelength band, extinction ratio, reflectance or transmittance of desired polarization and angular field are main characteristics of a PBS. Multilayer polarizing beam splitters are a kind of polarization separators that are based on optical interference thin films. Plate and cube are the main two configurations of thin film PBSs. In the plate type, the layers are deposited on a plane substrate while in the cubic form, the layers are deposited on the hypotenuse of two prisms and then these prisms are cemented together with an optical adhesive to produce a cube [1]. Fig. 1 shows a schematic view of a cubic PBS. There are good reviews on thin film PBSs in [2–4].

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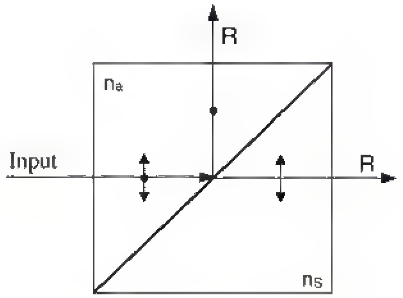

Fig. 1. Schematic view of a cubic PBS.

PBS is a main component in coherent optical communication systems based on the polarization diversity, optical instruments and other optical elements such as add/drop multiplexers, tunable acousto-optical filters and optical switching [4–10].

There are reports on the design of thin film polarizing beam splitters using different techniques [4,11,12]. From a general point of view, the design of a multilayer thin film filter (TFF) with an arbitrary spectral profile, is an optimization problem. Genetic algorithm (GA) is a powerful and attractive optimization tool and has been applied to several electromagnetic problems, including the multilayer optical filters since 1992 [13–20]. This method has an evolutionary nature and roots in genetic relations. We have used GA to design multilayer PBSs. In this paper, first, genetic algorithm is described as a design tool for multilayer filters. Then, thin film PBSs are designed using the GA and the results are presented and discussed and comparisons with other design techniques are given.

2. Genetic algorithm

Several optimization techniques have been used to design multilayer filters. From the optimization point of view, these techniques can be categorized into two types. First, methods that require an initial design on which the optimization is performed to obtain the desired specifications. Second, methods that start with a random design and then apply an optimization procedure on it. Genetic algorithm is a suitable and attractive tool for optimization and can be utilized as a design or optimization method to the thin film filters.

In an optimization problem, GA modifies the initial design parameters in a way that a better filter would be obtained through steps. In a design problem, this algorithm produces a set of initial designs named initial generation. Then, the genetic operators are applied to produce new generations with better specifications. Using this procedure, a suitable filter is finally obtained.

The basic block that GA works with is called "chromosome". In a TFF design problem, each chromosome is equivalent to a filter. A chromosome consists of "genes" that represent the refractive indices and thicknesses of the layers of a TFF. A "generation" is a set of chromosomes (filters) with various layers and N_{pop} is the number of filters in each generation. The numerical quality measure of a PBS filter is its "fitness function" which we have chosen as

$$F = \frac{1}{\sum\limits_{\lambda_i}(|R_S - 1| + |R_P|)}, \tag{1}$$

where λ_i is the wavelength of the ith sample and R_S and R_P are the reflectances for the S and P polarizations. Referring to Eq. (1), F would increase as R_S and R_P approach 1 and 0, respectively. A filter will be "stronger" if its F is greater.

The gene-based structure of chromosomes is shown in Fig. 2(a). Each chromosome (filter) consists of two gene strings, one string for refractive index of layers and one for layers thicknesses and these strings are interrelated for each filter. Here, refractive indices are selected from a predetermined set such as $\{n(1), n(2), \ldots, n(M)\}$ and the genetic operations are performed on the indices $1, 2, \ldots, M$ instead of the refractive index values (indexed variable). Layer thicknesses are integer variables measured in Angstroms. The GA based design procedure can be summarized as follows:

(1) *Creation of the initial generation.* In this step, N_{pop} filters with layer numbers between 1 to N_{max}, the refractive indices of layers chosen from the $\{n(1), n(2), \ldots, n(M)\}$ set and layer thicknesses in the $[d_{min}, d_{max}]$ interval are created randomly. The values of N_{max}, $n(1)$ to $n(M)$, d_{min} and d_{max} are defined by user.

(2) *Calculation of the fitness function (F) for each filter.* The fitness function is calculated for

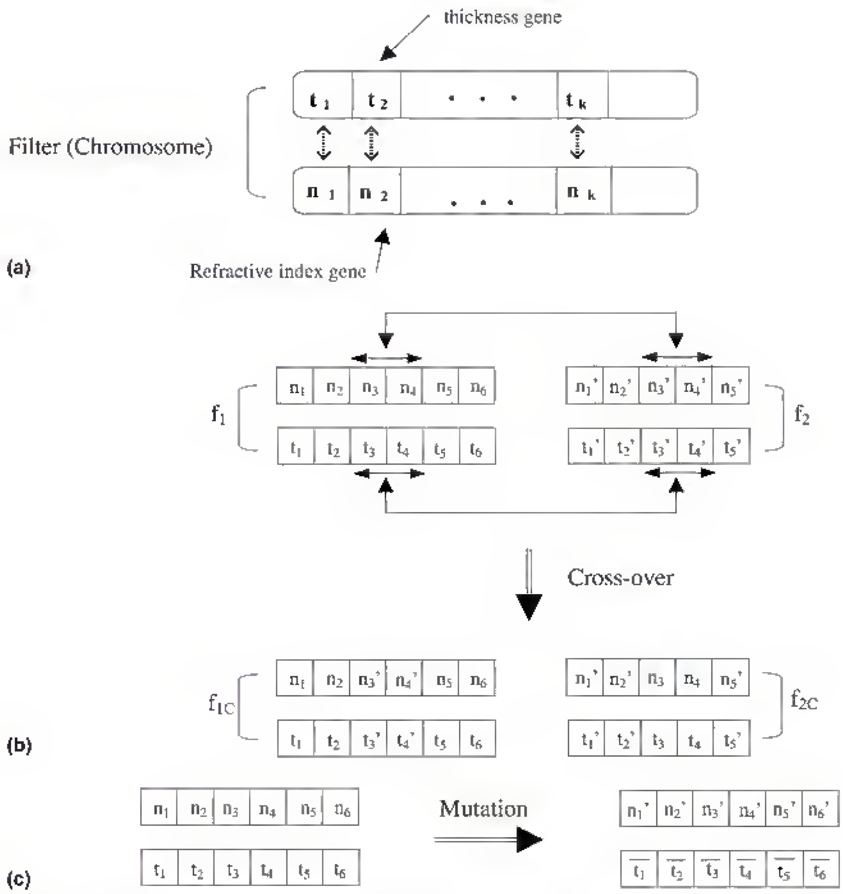

Fig. 2. (a) Chromosome (filter) structure of GA, (b) cross-over operator (c) mutation operator.

each filter using Eq. (1) and relations for thin film filter analysis [1]. Then, the filters are sorted according to their fitness function values (the strongest filter is at the top). Let F_d be a desired fitness function and F_S be the fitness function of the strongest filter in the current generation. Thus, if $F_S \geqslant F_d$, then the strongest filter is chosen as the desired filter and the operation is terminated. Otherwise, procedure is transferred to step 3.

(3) *Applying the genetic operators.* The genetic operators (selection, cross-over and mutation) are applied to the chromosomes according to the following steps. The number of chromosomes (filters) after applying each operator remains constant equal to N_{pop}. In these steps, G^k and G^{k+1} represent the current and the new generations, respectively.

(3.1) *Applying the selection (S) operator.* The selection operator consists of the natural selection and reproduction steps. In the natural selection step, the average of fitness functions is computed (F_a). Then, filters with fitness functions greater or equal to F_a are selected (N_1). After that, the remaining filters (($N_{pop} - N_1$) filters) are chosen through reproduction in which filters are selected randomly and proportional to their fitness function values. It means that the filters with higher fitness function value have more chance to select than the ones with lower fitness function. Also it is possible for weak filters to be selected according to random nature of this reproduction. Reproduction increases the density of strong filters in the selection stage. Thus we have

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$$G_S = S\{G^k\}. \quad (2)$$

(3.2) *Applying the cross-over (C) operator.* In this step, slices of refractive index genes and layer thickness genes are transferred between random selected pairs of filters. For this purpose, pairs of filters are selected randomly, then a slice with random length that is smaller than the length of the shorter filter, is defined over the two filters in each pair. Finally, the genes in this slice are transferred between two filters (Fig. 2(b)). Cross-over, basically, transfers genetic properties between chromosomes and after applying it we have

$$G_C = C\{G_S\}. \quad (3)$$

(3.3) *Applying the mutation (M) operator.* In this step, a few filters are chosen randomly and then their layer refractive indices and thicknesses are altered. The alteration procedure is to replace the current refractive index with one from the predetermined set. Also, the current layer thickness is subtracted from a predetermined value to produce a new layer thickness (Fig. 2(c)). Mutation is basically used for escaping from the local optima.

$$G_M = M\{G_C\}. \quad (4)$$

After applying all these operators, a new generation (G^{k+1}) is produced ($G^{k+1} = M\{C\{S\{G^k\}\}\}$) and the procedure continues by returning to step 2.

The above mentioned algorithm is implemented thorough a software in C++. Its inputs are: the refractive indices of materials, substrate and incident medium, the angle of incidence, the maximum and minimum allowable layer thicknesses and the maximum allowable number of layers. Also, the desired wavelengths and the corresponding desired R's are provided by the user. After completion of the design procedure, the structure of the filter is provided as a file.

3. Design results

In this section, we provide sample designs of multilayer PBSs, using the genetic algorithm. The first filter is a plate PBS. The target is to design a C-band plate PBS over 1528–1560 nm wavelength band. The angle of incidence is 60°, the incidence medium and substrate are air ($n = 1$) and BK7 glass ($n = 1.5$), respectively. Two materials with refractive indices of 1.465 (SiO_2) and 2.20 (TiO_2) have been used. Fig. 3 shows the profile of the designed filter which has 20 layers. Figs. 4 and 5 represent the percentage of reflectance versus wavelength and angle of incidence, respectively. The fitness function for this design has been equal to 5.25 for 10 wavelength points and 13,500 generations. The design took approximately 35 min on a PII/700 MHz computer.

To compare the results from GA with a previously designed classic PBS, a wide-band MacNeille PBS which is mentioned in [12], has been considered. This filter has 22 layers. The angle of incidence is 45° in prism, two materials with refractive

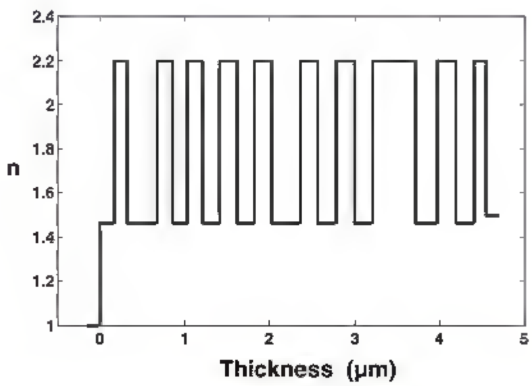

Fig. 3. Refractive index profile of the designed plate PBS.

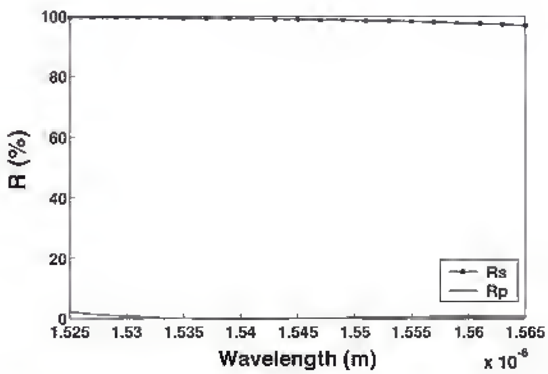

Fig. 4. Reflectance vs. the wavelength spectrum of the designed plate PBS.

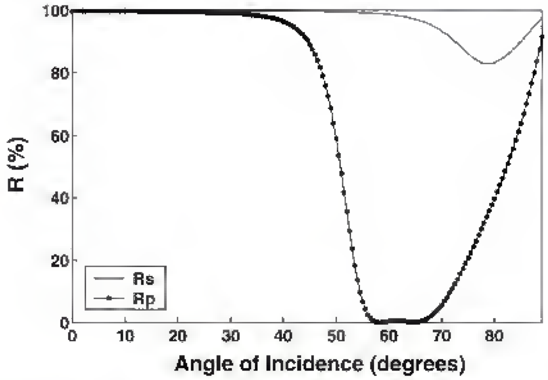

Fig. 5. Reflectance vs. the angle of incidence of the designed plate PBS at 1550 nm.

indices of 2.2 and 1.45 are is utilized and the refractive index of prisms is 1.7. Figs. 6(a, c) and 7(a) represent the calculated results and index profile of this PBS. For GA-designed PBS, it has been considered that angle of incidence is equal to 45° and the refractive indices of materials and prisms are the same as MacNeille one. Figs. 6(b, d) and 7(b) represent calculated results and index profile of this GA-designed PBS.

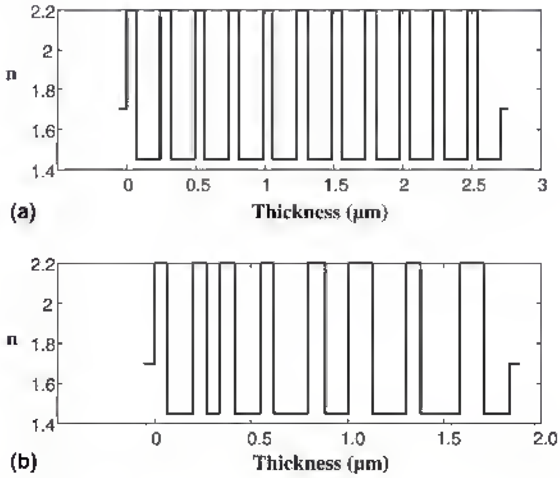

Fig. 7. Index profile of (a) MacNeille and (b) GA-designed PBSs.

As it is seen, the spectral characteristics of GA-based PBS is considerably better than MacNeille one and the total physical thickness of the former is less than the later PBS. Eq. (5), represents quality measure (P) for PBSs called degree of polarization [1]

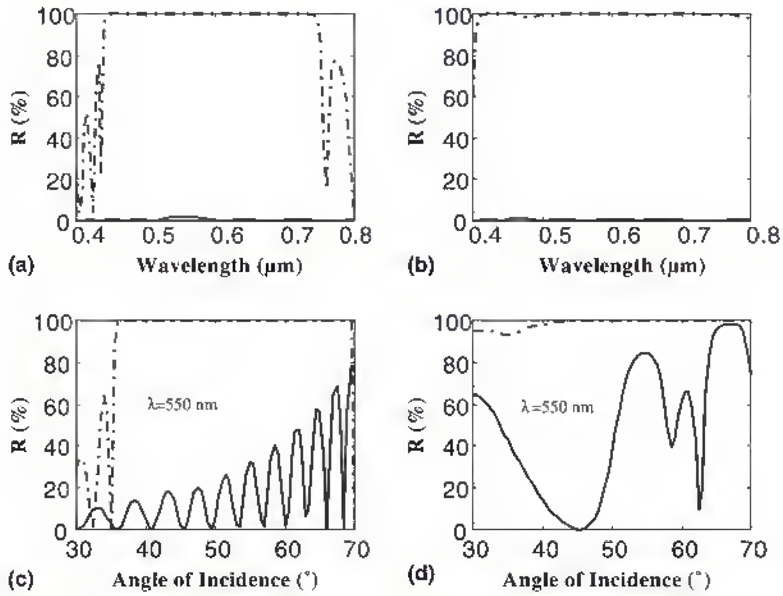

Fig. 6. Spectral profiles of MacNeille and GA-designed PBSs: (a, b) reflectance vs. wavelength and (c, d) reflectance vs angle of incidence in 550 nm for MacNeille and GA-designed PBSs, respectively (R_S: -·-, R_P: —).

$$P = \left| \frac{R_S - R_P}{R_S + R_P} \right|. \quad (5)$$

Considering P for comparing the quality of two PBSs for the desired wavelength band, Table 1 shows some parameters such as obtained wavelength band, angular sensitivity, total physical thickness as well as average and standard deviation of P. As it is seen, the GA-designed PBS has better performance based on the mentioned parameters. However, it should be noted that because of the random nature of GA, in a predetermined execution time, it is required to design some PBSs and then select the best one.

The third PBS is a cubic one. This PBS has been designed as a C-band (1528–1560 nm) polarization splitter which has applications in WDM optical communication systems. The angle of incidence is 45° in prism, the refractive indices of incident and substrate mediums are 1.5 (BK7 glass) and a maximum of 20 layers is allowed. For manufacturing purposes only two materials with refractive indices of 1.465 (SiO_2) and 2.065 (Ta_2O_5) have been used. The designed filter has 19 layers. The fitness function for this design has been equal to 28.65 for 10 wavelength points and 13,400 generations. The design took approximately 25 min on a PII/700 MHz computer. Also for comparing the designs with GA and other synthesis techniques, the third example (C-band cube PBS) has been considered and compared with the results obtained from major synthesis techniques such as needle [21], flip-flop [22] and combined GA and gradient methods. For needle and flip-flop designs, the FilmWizard from Scientific Computing International (SCI) has been utilized in which the mentioned synthesis methods exist. Table 2 represents the results obtained from these methods. In all designs, the angle of incidence, refractive indices of materials, incidence medium and substrate are the same as GA designed filter.

In needle design, initial total thickness, maximum layer numbers and minimum layer thickness are set to be 6000 nm, 20 and 10 nm, respectively. The result for 50 iterations is a 20 layer PBS. This design took 1 min on the above mentioned computer. In flip-flop design, the initial total thickness, maximum layer numbers and minimum layer thickness are set to be the same as needle design and the mesh size is 10 nm. The result for 25 iterations is a 19 layer PBS. This design took 30 s on the above mentioned computer. The last design is based on the combination of GA and gradient methods to lower the design time of the basic GA method. For this purpose, the result of first 200 generations of the GA program, that had 17 layers and took 2 min, has been optimized with the global gradient method. The optimization process had 100 iterations and took 3 min. Figs. 8–11 represent the dependency of spectral characteristics of the above PBSs on wavelength and angle of incidence.

For considering the effect of manufacturing issues on the designed filters, the layer thicknesses of each filter has been perturbed 100 times with random changes of ±5 Å. Then, for each perturbation, the average of P over desired bandwidth has been compared with the average of P for un-

Table 1
A comparison between some parameters of MacNeille and GA-designed PBSs

	Angle of incidence (°) (in glass)	P_{ave} (%)	σ_P^* (%)	Effective wavelength band (nm) ($P > 95\%$)	Angular sensitivity (°)	Total physical thickness (μm)
GA-designed PBS	44	96.39	2.438	∼400		
	44.5	98.07	1.346	∼400		
	45	99.06	0.661	∼400	2	1.8
	45.5	99.26	0.521	∼400		
	46	98.6	0.938	∼400		
MacNeille PBS	45	98.25	3.447	∼375		
	45.5	97.61	8.074	∼375	1	2.7
	46	96.83	7.87	∼375		

*Standard deviation of P over desired wavelength band.

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Table 2
Comparison among various design techniques for a cubic C-band PBS

	GA		Needle		Flip-flop		GA + gradient	
	d (Å)	n	d (Å)	n	d (Å)	n	d (Å)	n
Structure	A	1.5	A	1.5	A	1.5	A	1.5
	2237	2.065	3178.2	1.465	13,600	1.465	2096.8	2.065
	2730	1.465	2364.7	2.065	1500	2.065	2708.3	1.465
	2207	2.065	4464.7	1.465	3500	1.465	2031.5	2.065
	2313	1.465	2605.6	2.065	2000	2.065	3154	1.465
	2144	2.065	4796.1	1.465	4600	1.465	1840.5	2.065
	2587	1.465	2482.2	2.065	1400	2.065	3322.8	1.465
	2275	2.065	11997	1.465	2600	1.465	2003	2.065
	2731	1.465	2361.3	2.065	1500	2.065	3303.9	1.465
	2343	2.065	4163.6	1.465	6100	1.465	1835.4	2.065
	3933	1.465	2334.7	2.065	800	2.065	4130.5	1.465
	2017	2.065	4089.3	1.465	5000	1.465	1706.8	2.065
	2946	1.465	2417.6	2.065	1900	2.065	3493.8	1.465
	2322	2.065	3976.4	1.465	2000	1.465	1803.3	2.065
	2347	1.465	2518	2.065	2700	2.065	3142.9	1.465
	2177	2.065	4343.4	1.465	2700	1.465	1988	2.065
	3084	1.465	2864.7	2.065	2000	2.065	2846.5	1.465
	1625	2.065	3553.6	1.465	3300	1.465	2062.8	2.065
	3033	1.465	2892.9	2.065	1800	2.065	S	1.5
	2321	2.065	4285	1.465	600	1.465		
	S	1.5	2392	2.065	S	1.5		
			S	1.5				
$\sum d$ (μm)	4.7372		7.4081		5.96		4.3471	
$\sum(nd)$ (μm)	8.2401		12.367		9.6674		7.6104	
Max. (P)	1.0		1.0		0.9995		1.0	
Min. (P)	0.9954		0.9930		0.9710		0.9898	
Mean (P)	0.9986		0.9980		0.9927		0.9968	
Std. (P)	0.0012		0.0016		0.0077		0.0028	
Layer number	19		20		19		17	
Yield (%)	100		100		2		9	
Design time	25 min		1 min		1/2 min		5 min	

A, incident medium; S, substrate; P, degree of polarization; Std., standard deviation.

perturbed filter. If the absolute change is less than 0.005, the filter is selected and otherwise rejected. These calculations have been brought in Table 2 under "Yield" item. Considering the results in Table 2 and Figs. 8–11, the best results belong to GA and needle methods. Although the GA is a powerful optimization tool and searches for the global optimum point, when its search space becomes very large and complicated, the design time increases considerably and in comparison with other methods may bring a drawback to GA. The design time is highly dependent on the number of wavelength points, maximum number of layers and the maximum layer thickness. In simpler designs such as antireflection filters, GA is able to

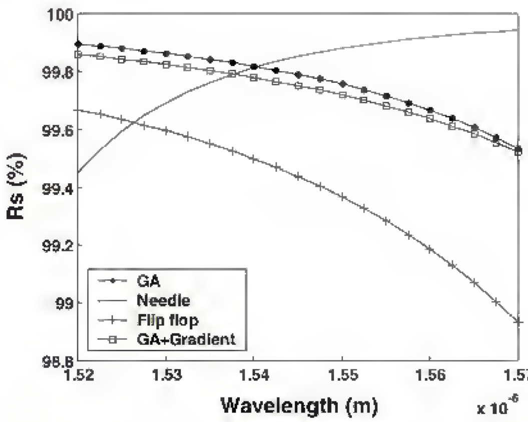

Fig. 8. S-polarization reflectance (R_S) for various design methods for the C-band cubic PBS.

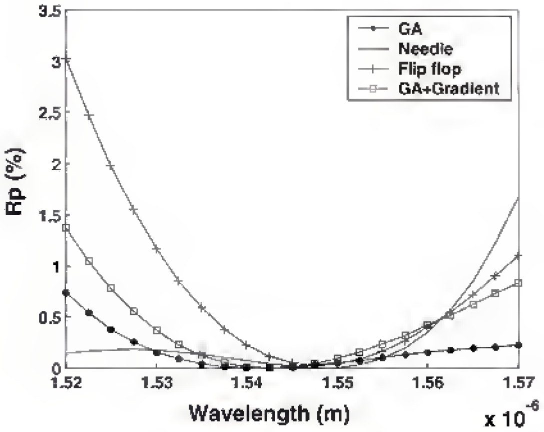

Fig. 9. P-polarization reflectance (R_P) for various design methods for the C-band cubic PBS.

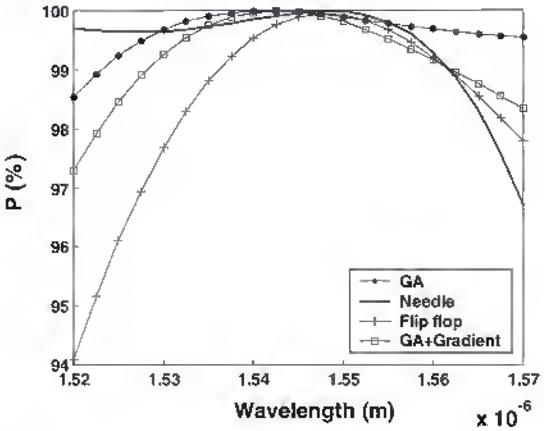

Fig. 10. Degree of polarization (P) for C-band cubic PBS vs. wavelength for various design methods.

produce an optimum design, similar to other well-known methods, in a few seconds.

4. Conclusions

In this paper, the genetic algorithm optimization technique has been used to design multilayer PBSs. For design, only the optimization of reflectances of S and P polarizations over a predetermined wavelength-band have been considered and the materials are considered to be perfect dielectrics. First, for evaluating GA to design PBSs, a plate PBS has been designed over a wavelength-band which is suitable for WDM optical communication systems. The plate PBS has 20 layers with wavelength band of 1528–1560 nm. This design, shows the ability of GA in providing results with suitable agreements with desired specifications. For comparison with classic designs, a cube PBS has been designed and compared with similar MacNeille one. Based on the results in Table 1 and considering degree of polarization as a measure of comparison, the wavelength band, angular sensitivity and the total physical thickness of the GA-designed PBS are better than the MacNeille one. Table 1 represents a summery of some of these parameters based on P, angle of incidence and spectral band of the two mentioned PBSs. As it is seen, the designed PBS has better spectral profile as well as less total physical thickness with respect to MacNeille one. Considering other synthesis techniques, a C-band cube PBS has been designed using GA, needle, flip-flop and combined GA and gradient optimization methods with similar design parameters and targets. As it is seen in Figs. 8–11 and Table 2 and the information in the previous section, GA and Needle methods have represented the best results. From the reported results and other designs with the GA, it is observed that for filters that have complicated profile or do not have a classical or straight method of design, GA is a

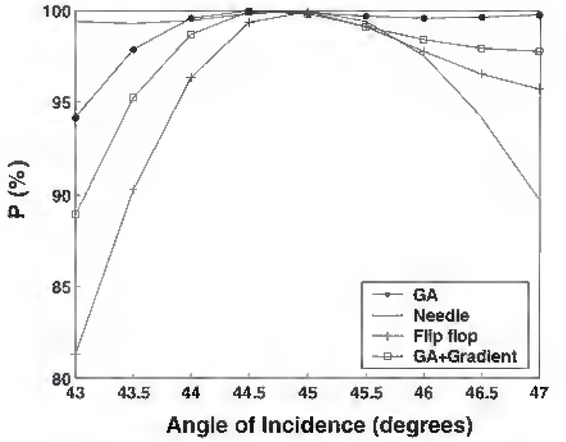

Fig. 11. Degree of polarization (P) for C-band cubic PBS versus angle of incidence in prism.

suitable design tool when the design time is not a critical parameter. The choice of some design parameters such as layer thickness range, maximum number of layers and wavelength points have direct effect on the optimization process. So, the user of the GA should take into account the effect of the mentioned parameters.

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